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論　文

[2220] Nonlinear Response of RC In-Plane Structures Surrounded by Soil Continuum under Shear

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1. INTRODUCTION

In the design of underground RC structures, soil and RC structures are basically treated as independent systems. This is due to the insufficient knowledge about the interaction between the soil and RC structures especially in the elasto-plastic stages. Several researches were undergone on underground structures subjected to seismic loading[1]. These researches considered low stress levels which are close to the elastic range. As a result, underground structures have high structural stiffness and high factor of safety which would bring uneconomical decision and lower ductility of structures in some cases. This paper treats underground RC structures subjected to high shear deformation through surrounding soil medium.

In present design practice, the earth pressure is generally specified independent on the structural deformations and types. But, it was clearly proved through experiments that the induced force from surrounding soil varies according to the structural nonlinearity of RC[2]. For rationale design of underground structures, the possible mode of failure of RC underground should be known. In this paper, numerical parametric FEM analysis is carried out to investigate the change in the response due to the nonlinearity of RC shell type structures (tanks, ducts, cason...) surrounded by soil medium under high shear transferred through the surrounding soil. Due to these loads, the nonlinearity of the RC structure is induced by cracking of concrete and yield of reinforcement. From this analysis, failure mode, residual deformation and nonlinearity of underground structures are investigated to obtain rationalized guidelines for the future improvement of underground structural design.

2. DEFINITION OF THE PROBLEM

In this study, RC under-ground duct with height (H = 15.0 m) and box cross section (L x L = 5.0 x 5.0 m) with thickness (d) and surrounded by soil continuum is studied. The RC duct coupled with surrounding medium is analyzed under the shear mode denoted by (δ) acting on the soil as shown in Fig(1). In the analysis, the soil is considered as linear elastic material with Young's Modules E_{soil} to clearly know the possible failure condition of RC structure. Assumption of elastic soil medium is severe to the failure condition of RC since no damage is made in soil. Various parameters are considered in the analysis in order to study the deformation mode of the RC structure in the nonlinear stage.

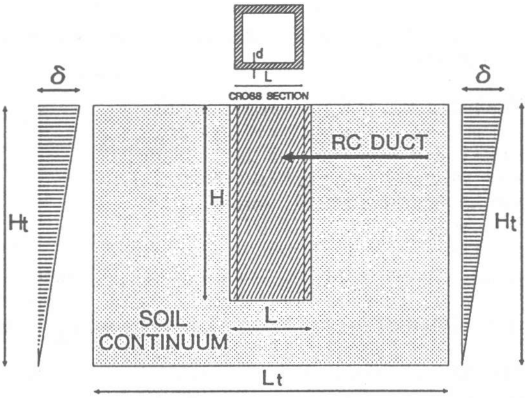

FIG.(1) *ENTIRE SYSTEM*

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3. DESCRIPTION OF THE ANALYSIS

The Computer Program "WCOMR"[3] is used in this study. It is based on the finite element method with two-dimensional quadrilateral 8-nodes isoparametric elements. Nonlinear solution technique enables a step by step loading of a structure. An iterative procedure is performed at each load step until equilibrium requirement is satisfied. It provides the information about deformations, stresses, crack development and failure modes (crushing of concrete and reinforcement yielding) at each load step. The post-peak behavior of the structure is obtainable under reversed cyclic loads.

In "WCOMR", the nonlinearity of reinforced concrete depends on the bond between reinforcement and concrete, compressive characteristics of concrete between cracks and shear transfer behavior of cracks. The reinforced concrete plate element model was constructed by combining the constitutive law of both concrete and reinforcing bars. The constitutive law adopted for the smeared crack concrete is composed of the tension stiffening model, the compression model and shear transfer model [3]. The constitutive laws for smeared crack RC model was systematically verified, as a result of which laboratory experimentation for in-plane members and structure can be replaced by numerical simulation.

The finite element mesh, composed of eight node quadrilateral elements is used as shown in Fig(2). In the analysis, the mean shear displacement ($\gamma = \delta/H_t$) is applied incrementally up to a maximum of 2.0 % (severe earthquake) or failure. The mechanical properties of surrounding Soil[4] are represented by Young's Modules (E_{soil}) which varies from very weak soil (250 *kgf/cm*^{2}) to very stiff soil (5000 *kgf/cm*^{2}) . The RC structural rigidity, as represented by the ratio of the thickness to the length of the wall (d/L), is changed from 0.025 to 0.3. The reinforcement ratio of the RC structure is considered isotropic ($P_x = P_y$) and ranges from 0.3 to 2.0%. The interface between the soil elements and RC elements is assumed totally fixed (no separation and no sliding), which is also a severe condition concerning RC failure.

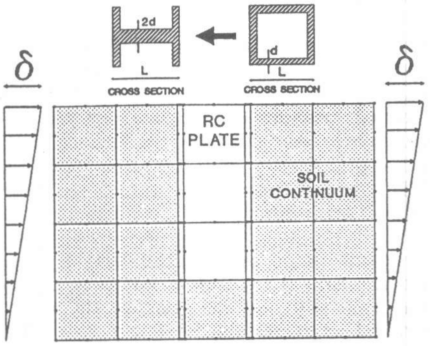

FIG.(2) *FINITE ELEMENT MESH*

4. NONLINEAR RC RESPONSE UNDER CONTINUUM MEDIA

4.1. STRUCTURAL INDICATORS OF STRESS, STRAIN AND DAMAGES

Stress and strain tensors invariants[5] are used as indicators to identify the response mode and cracking condition.

$$I_1' = \epsilon_1 + \epsilon_2 = \Delta V \,/\, V \qquad \text{(local)}$$

$$I' = \int_{elements} I_1'(x,y)\; dx\, dy \,/\, A \quad .... \quad .... \text{ (structure based average)} \qquad (1)$$

The first strain tensor invariant denoted by (I_1') is closely associated with the crack occurrence and expansion of the in-plane element (volumetric change of the element). ***Spatially average first strain invariant*** (I') is the average of (I_1') for all the RC elements. This average is used as an indicator for the volumetric change of the RC structure within 2D plane. This value is equal zero in case of elastic shear (no volumetric change). The authors accepted the volumetric averaging (I') of the local intensity of expansive deformation which has much to do with leakage resistance and structural soundness.

$$J_2' = |\epsilon_1 - \epsilon_2| \qquad \text{(local intensity of shear)}$$

$$J' = \int_{elements} J_2'(x,y)\; dx\, dy \,/\, A \quad .... \quad .... \text{ (structure based average)} \qquad (2)$$

The second strain deviator invariant denoted by (J_2') is used as indicator of shear mode of the deformation of the in-plane element which is closely connected with induced shear force. The authors used the ratio of ***spatially averaged second strain deviator*** (J') of RC structure with respect to

(J′) of surrounding soil as a whole, as an indicator for the relative intensity of shear deformation of RC in soil which is represented by (J'_{str}/J'_{soil}) in this paper.

Spatially average second stress deviator (J) is defined as indicator of the average shear stress level for the whole RC structure. By using (J) and cross section area of RC, the average shear force acting in the RC from surrounding soil (V) can be calculated as shown in Eqn. (3).

$$J_2 = \sqrt{\frac{1}{3}\left[(\sigma_1-\sigma_2)^2 + \sigma_1\sigma_2\right]} \qquad \textit{(local)}$$

$$J = \int_{elements} J_2(x,y)\, dx\, dy \,/\, A \quad .... \qquad (3)$$

$$.... \quad \textit{(structure based average)}$$

$$V_{average} = J * (\textit{cross section area of RC})$$

Equations (1), (2) and (3) show the relations of (I′), (J′), (J) and (V) where; (ϵ_1) and (ϵ_2) are the local principal strains. (I_1') is the local first strain invariant. (A) is the total area of RC elements. (I′) is averaged first strain invariant of RC elements. (J_2') is the local second strain deviator invariant. (J′) is the average second strain deviator. (J_2) is the local second stress deviator invariant. (σ_1) & (σ_2) are the local principle stresses. (J) is the average second stress deviator of RC element, and (V) is the average shear force induced in the RC.

4.2 NONLINEARITY OF STRUCTURE

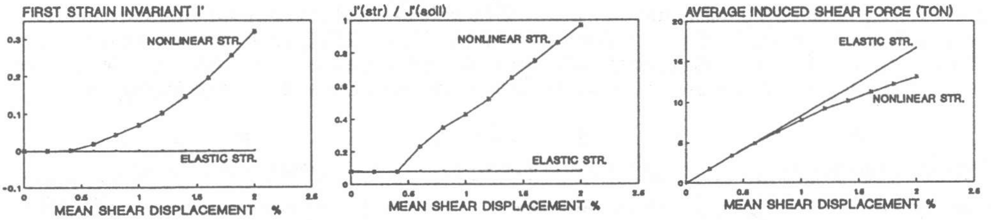

FIG.(3) *EFFECT OF NONLINEARITY OF STRUCTURE*

Two problems were discussed, ie. nonlinear RC structural and linear assumed structures, to clarify the effect of the RC nonlinearity on the damage criteria. The problem parameters are; E_{soil} = 1000 *kgf/cm²*, $P_x = P_y = 0.5$ %, $E_{concrete}$ = 200000 *kgf/cm²* and d/L = 0.05. Fig.(3) summarizes the results of the analysis. It can be seen that, for mean shear displacement $\gamma \leq 0.4$ % both curves for linear and nonlinear assumptions of RC coincide. In this range, the structure behavior is elastic in both cases and the nonlinearity does not take place yet. In case of mean shear displacement > 0.4 %, by checking the cracking condition through *I′*, the elastic analysis of structures gives rise to the zero volumetric change (no crack). But in case of nonlinear analysis of RC, its value is increasing exponential with the shear displacement. By comparing the intensity of shear deformation of RC in soil, it is found that the elastic analysis brings constant the ratio (J'_{str}/J'_{soil}) with increasing mean shear displacement. In the second case, (J'_{str}/J'_{soil}) increases with increasing γ and it becomes about 10 times more than elastic analysis at γ = 2.0 %. The induced shear force to the RC from surrounding soil gets less owing to nonlinear structural response and its difference becomes more significant for high shear displacement (about 25%).

5. ANALYTICAL RESULTS AND DISCUSSION

The problem parameters are arranged to cover the combinations of the parameters in the following ranges, which resulted in the solution of 168 cases, as,

E_{soil} *kgf/cm²*	250	1000	2000	3000	4000	5000	
d/l	0.025	0.050	0.100	0.150	0.200	0.250	0.300
$P_x = P_y$	0.3 %	0.5 %	1.0 %	2.0 %			

5.1 DAMAGE RELATED TO THE STRUCTURAL SOUNDNESS

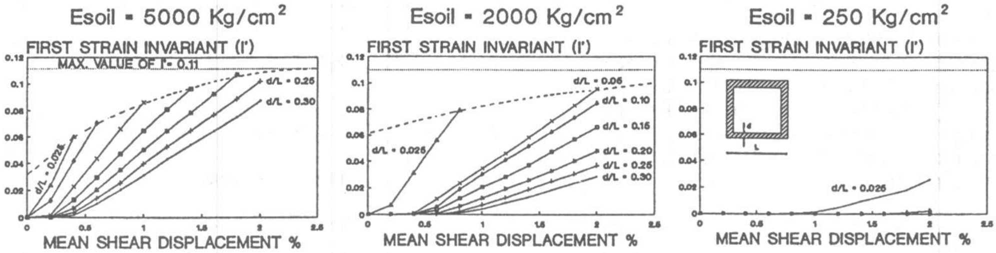

FIG.(4) *EFFECT OF SURROUNDING SOIL MEDIUM ON THE FIRST STRAIN INVARIANT*

Fig.(4) shows the relation between the intensity of expansive deformation in terms of first strain invariant (*I'*) and mean shear displacement γ for different rigidity of the structure and different surrounding soil medium at constant reinforcement ratio ($P_x = P_y = 2.0$ %). In case of very stiff soil (E_{soil} = 5000 *kgf/cm²*) most of the cases for different d/L have a failure condition at mean shear displacement γ ≤ 2.0 %. The envelope of failure is increasing with γ until 2.0 %. If any structure has the volumetric expansion induced by cracks under the envelope at certain γ ≤ 2.o %, this structure can survive under any value of shear displacement with certain level of deformation and cracking. In this case, it is very important to consider the serviceability of the structure in the design to decide the acceptance level of cracking. By decreasing the stiffness of the surrounding soil (E_{soil}), the value of (*I'*) has the same behavior with decreasing value of (*I'*) maximum. For E_{soil} = 2000 *kgf/cm²* (medium soil), no failure occurs till γ = 2.0 % unless d/L is equal 0.025 or less. For very weak soil (E_{soil} = 250 *kgf/cm²*), the structure does not fail for any value of d/L or reinforcement ratio. From the above mention, it can be conclude that the intensity of expansive deformation is so much dependent on the stiffness of the surrounding soil.

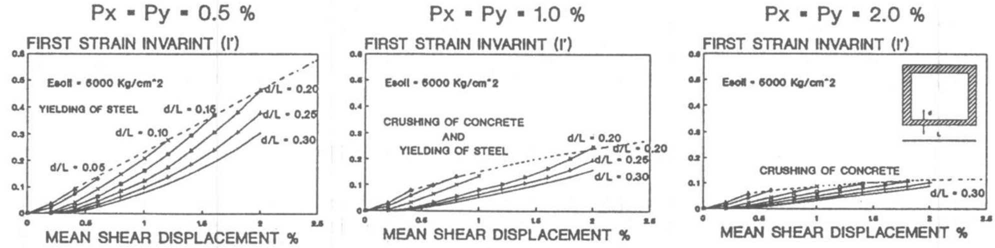

FIG.(5) *EFFECT OF REINFORCEMENT RATIO ON FIRST STRAIN INVARIANT*

As for reinforcement ratio, the relationship between first strain invariant (*I'*) and mean shear displacement γ for different reinforcement ratios at E_{soil} = 5000 *kgf/cm²* is shown in Fig.(5). By decreasing the reinforcement ratio, the gradient of the envelope of failure increases greatly and the maximum value of (*I'*) is increasing, for the same value of γ. If any particular case under envelope is compared for different reinforcement ratios, the crack opening mode of deformation expressed by (*I'*) becomes less by increasing reinforcement ratio. This means less cracks and less ductility. From this results, the reinforcement ratio is the main controller for the intensity of expansive deformation (volumetric change).

5.2 STRUCTURAL SHEAR OF RC IN SOIL CONTINUUM

Fig.(6) shows the relation between the relative intensity of shear deformation of RC in soil, which is represented by (J'_{str}/J'_{soil}) and mean shear displacement γ, for different structure rigidity and different reinforcement ratio at constant surrounding soil media. The intensity of shear deformation of RC (J'_{str}/J'_{soil}) increases proportional to the mean shear displacement γ. On the other hand, it decreases with increasing in the thickness of the structure d/L. The failure envelope for (J'_{str}/J'_{soil}) is decreasing with increasing γ up to a certain minimum value. If the value of (J'_{str}/J'_{soil}) is less than envelope values, the structure does not fail under any condition. The envelope curve is nearly the same for certain value of reinforcement ratio and varies with reinforcement ratio.

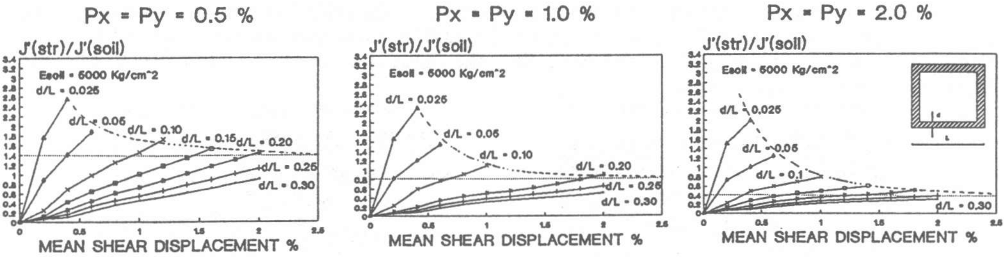

FIG.(6) *EFFECT OF REINFORCEMENT RATIO ON SECOND STRAIN DEVIATOR* (J'_{str}/J'_{soil})

The effect of reinforcement ratio is shown in Fig.(6). The trend of the envelope curve of failure is the same for different values of reinforcement ratio as it decays to minimum, but the minimum value of (J'_{str}/J'_{soil}) is different. This value is maximum for reinforcement ratio equal to 0.5 % and decreases by increasing the reinforcement ratio. Also, in case of low rigidity of structure (d/L $<$ 0.1) the shear deformation is nearly the same with different reinforcement ratio, but for high rigidity of RC (d/L $>$ 0.1) the shear deformation is so much decreasing by increasing reinforcement ratio. For high reinforcement ratio (2.0%) the shear force induced to the RC is nearly constant (FIG.7) with increasing the rigidity of structure and the strength of the structure increase so much because the shear deformation of the RC decreases. Reinforcement ratio is one of the factors in determining the intensity of shear deformation of RC in response to the surrounding soil deformations.

5.3 INDUCED SHEAR FORCE FROM SURROUNDING MEDIUM

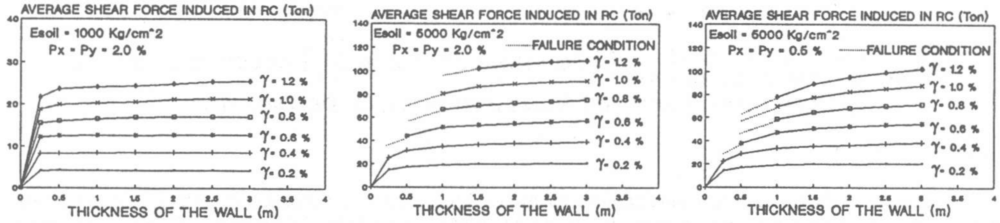

FIG.(7) *EFFECT OF THE REINFORCEMENT RATIO AND SURROUNDING SOIL ON THE INDUCED SHEAR FORCE IN RC*

Fig.(7) shows the relation between shear force induced in the RC wall (V) and the thickness of the wall for different mean shear displacement γ. In case of weak soil, the induced shear force to RC from surrounding medium is nearly constant even if thickness and rigidity of RC are widely changed. On the other hand, for stiff soil the induced force to RC increases rapidly for small rigidity till thickness gets equal to 1.5 m. By decreasing the reinforcement ratio the effect of the thickness gets significant. In the design of underground structure, the rigidity of the structure has significant effect on the induced force in the RC structure from rigid surrounding soil. This means that the applied load to underground RC depends on the feature of structure itself,and especially, on the mechanical stiffness of soil.

5.4 FAILURE MODE AND INDUCED DEFORMATION

From the results of the current analysis, the mapping of failure of RC underground structures are concluded for different parameters as shown in Fig.(8). These charts are drawn for maximum mean shear displacement 2.0 %. In each chart, the X-axis represents the stiffness of surrounding soil. The Y-axis represents the rigidity of structure in terms of (d/L). The contour lines in each figure represent different intensity of expansion deformation in terms of (I'). The hatched area represents the structures which failed. This area is divided into three parts. First area is unallowed area for design based on the present design practice (minmum thickness of wall d/L = 1/30). Second area, the structure has failure mode of crush concrete but last area by yielding of steel. Above the hatched area, for any point, the structure can survive under any value of shear displacement less than the maximum of shear displacement but with different crack opening. From this chart, it can be seen that the reinforcement ratio has great effect on the intensity of the expansion deformation and crack opening. On the other hand, the reinforcement ratio does not change the boundary of failure of structure, because by increasing the reinforcement ratio, the strength of the RC increases. But, at the same time the induced force level in the structure is also elevated by the same proportional.

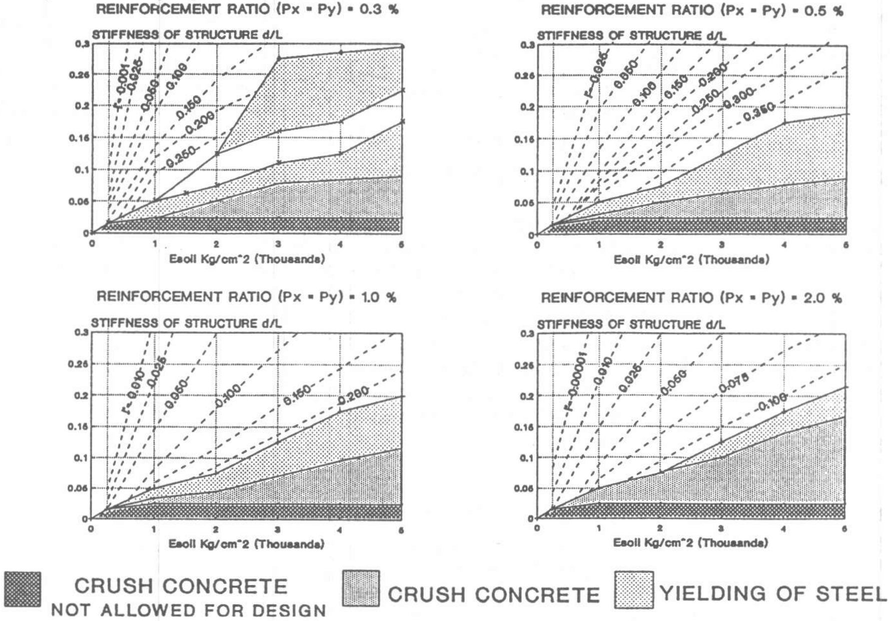

FIG.(8) ***MAP OF FAILURE MODE AND INDUCED DEFORMATION***

6. CONCLUSIONS

In case of safety of underground structures under high shear deformation of whole soil-structure system, the rigidity of the structure and surrounding soil are closely interlinked in deciding the thickness of RC. However, in present design practice, the minimum thickness of structure is computed based on an earth pressure, which is taken constant and independent of structural stiffness and the soil rigidity.

The applied load to underground RC depends on the feature of Structure itself and especially on the mechanical stiffness of soil. The intensity of expansive deformation and crack condition is controlled mainly by reinforcement ratio and also dependent on the stiffness of the surrounding soil.

As a matter of fact, changing reinforcement ratio is not very effective as for safety of the structure. The structural strength and induced force from surrounding soil increase proportionally. But the reinforcement ratio has great effect on the soundness of the structure. Deciding the reinforcement ratio should be done in terms of the function and serviceability of the underground structure.

The concept of designing underground structures may be further improved in terms of the safety, dynamic load estimation and the design function of structure.

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